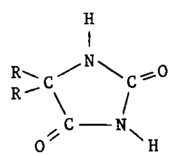
THE MECHANISM OF THE FORMATION OF HYDANTOINS

J.J. Worman, K. Uhrich, E. Olson, J. Diehl
S. Farnum, and S. Hawthorne

University of North Dakota Energy Research Center
Box 8213, University Station
Grand Forks, North Dakota 58202

Introduction

Hydantions, (I), are biologically active compounds which occur in nature and have been isolated from such sources as sugar beets and butterfly wings. Synthetic analogs have found widespread use as anticonvulsant drugs, bacteriocides, stabilizers in photographic film, and in the preparation of high temperature epoxy resins. Uses, preparation, and reactions of hydantoins have been extensively studied and are reported elsewhere (1, 2).



(I)

Recently a number of hydantoin isomers have been detected and identified in coal gasification condensate water from the gasification of Indian Head (ND) lignite at the University of North Dakota Energy Research Center in a slagging fixed bed gasifier (3). The hydantoins constitute a major portion of the organics in the condensate water and have recently been identified in water from other gasification processes (5). In general the concentrations of hydantoins found in the condensate water from an ash gasifier are smaller than those found from the slagging process. There is also a relationship between the type of coal used and the amount of hydantoins formed. Lignite coal reacting in a slagging gasifier gives the largest concentration of hydantoins in the condensate water. The major isomer in the coal gasification condensate water is 5,5-dimethylhydantoin (DMH). It should be emphasized that DMH is formed from individual species (acetone, cyanide, ammonia, and carbonate) in the condensate water and does not form directly in the gasifier. Hydantoins were shown to be either absent or present in low concentrations in water samples which were collected from side-stream samples in the UNDERC gasifier and quickly frozen. When this sidestream condensed water was heated in a constant temperature bath of 40°C, DMH concentrations increased in an approximately second order manner (6). The formation is believed to proceed by the Bucherer-Berg reaction, the same reaction used for commerical hydantoin synthesis (3).

The potential use of the slagger to produce economically useful synthetic fuel gas, both on the national and international scale, prompted an investigation into the kinetics and mechanisms of formation of DMH. It was impossible to obtain reliable and reproducible concentration data for acetone and cyanide in the raw gasifier condensate water due to reversible addition products (acetone cyanohydrin, etc), so a model system was chosen. Acetone cyanohydrin was reacted with excess ammonium carbonate at concentrations approaching those obtained in the condensate water. The experimental details and results have been recently reported (7). The rate of formation of DMH was first order in all of the reactants as expressed by Equation 1.

$$\text{Rate of formation of DMH} = [\text{Acetone}]\,[\text{HCN}]\,[NH_3]\,[CO_2] \qquad 1)$$

This kinetic data is valuable in predicting the rate of formation of DMH in coal gasification condensate water, provided the model is applicable. The pH of the model solution and the condensate water remained constant at around 8.4, but the effects of small changes in pH on the rate are not fully known.

A mechanism consistent with the kinetic data and partially verified by others is shown in Scheme 1 (8, 9, 10). What remains to be studied is to obtain detailed evidence of the rate-determining step and to isolate intermediates VI, VII, and VIII. In this work we will show that the carbamate salt which results from the reaction of two moles of α-aminoisobutyronitrile with carbon dioxide gives an N-substituted hydantoin rather than the expected DMH. This either precludes the salt as forming in the gasifier water since the N-substituted hydantoins has not been identified in gasifier condensate water, or the salt reacts rapidly by an alternate mechanism to give DMH.

Experimental

α-Aminoisobutyronitrile (IV) - Ammonia gas was bubbled into 50 ml of acetone cyanohydrin (Aldrich) at 60°C for several hours. The product was distilled at 50-56° (20 mm) to give 90 percent yield. The structure was verified by IR, Mass Spec. and ^{13}C NMR. The product was stored under nitrogen and refrigerated to prevent slow reverse hydrolysis and discoloration.

2-Cyanopropyl-ammonium 2-Cyanopropyl-2-Amino Carbamate (X). - Dry ice was added slowly to a 25-ml neat sample of α-aminoisobutyronitrile. This was continued until the entire system was solid, about one hour. Anhydrous ether was added and the mixture stirred and filtered. The resulting white solid reacts with dilute hydrochloric acid to give the starting aminonitrile hydrochloride salt and carbon dioxide. The carbamate had a m.p. of 210°C and gave peaks at m/e 212 and 168 via solid probe mass spectrometry. On hydrolysis, the compound gave acetone, ammonia, acetone cyanohydrin, and α-aminoisobutyonitrile as indicated by GC/MS.

N-α-Carbamylisopropyl-N'-α-isobutyronitrile urea (XI)

A) Carbon dioxide was bubbled through a neat sample of a α-Aminoisobutyronitrile at room temperature. After one hour, the entire sample was solid. This solid was filtered and washed thoroughly with anhydrous ether to remove any unreacted starting material. All spectral properties and elemental analyses were consistant with the structure. The m.p. was identical to the structure proposed by Bucherer (8).

B) Compound X was allowed to stand at room temperature for several days and after analysis proved to be identical to XI in all respects.

3-(α-Carbamylisopropyl)-5,5-dimethylhydantoin (XIII) - The N-substituted urea, XI, was allowed to stand at room temperature in water for 24 hours. The reaction was followed by ultraviolet spectroscopy and by gas chromatography which indicated the formation of an intermediate that disappeared slowly to give the final product. After evaporation of the water in a vacuum, the resulting white solid (50% yield) was identified as 3-(α-carbamylisopropyl)-5,5-dimethylhydantoin (XIII). The structure was verified by ^{13}C-NMR and single crystal x-ray analysis. The properties of the solid were identical in all respects to that of a sample prepared by an alternate synthesis (11). The high resolution mass spectrum gave the correct molecular formula and a molecular ion of m/e 213 and a base peak at m/e 169.

Results and Discussion

In order to clarify further the mechanism of formation of DMH shown in Scheme 1, an attempt was made to isolate the carbamic acid salt of X. When solid dry ice was added to α-aminoisobutyronitrile, a white solid was isolated which by IR, mass spectrometry, elemental analysis, and its reaction with water and hydrochloric acid was best represented by structure XI. Salts of carbamic acids of similar structure have been reported previously and are more or less stable, depending on their specific structure (12). The carbamate X slowly rearranged at room temperature to the disubstituted urea, XI, shown in Scheme 2. This urea was also prepared by bubbling carbon dioxide gas through α-aminoisobutyronitrile at room temperature.

The compound was reported previously (8). Its structure was verified by spectroscopic techniques and elemental analysis.

What occurred next was unexpected. When the N, N'-disubstituted urea was placed in water at room temperature, changes began to take place. The ultraviolet absorption spectrum showed a gradual increase in an absorption at 257 nm. This peak began to disappear after twelve hours and after twenty-four hours was absent from the spectrum. GC analysis using a cool, on-column injection onto a 30 m OV-351 fused silica capillary column gave, as a major compound, the N-substituted hydantoin, XIII. The structure of XIII was proven by alternate synthesis, elemental and spectral analysis, and single crystal X-ray analysis. The carbamate salt in water gave similar results. Only trace amounts of DMH were observed by GC/MS.

The mechanism for the formation of the N-substituted hydantoin is shown in Scheme 2. Evidence for the structure of the bicyclic imino intermediate (XII) is based on several factors. The ultraviolet absorption spectrum is consistent with an n π^* transition of an imine chromophore occurring at 257 nm (13) and the GC/MS of the intermediate gave a peak at m/e 195. This represented a loss of ammonia from the starting N-substitute area, XI. The absence of a fragment peak at m/e 151 (m-44) is strong evidence that the intermediate, XII, does not contain a carbonyl or carboxyl group. That this highly strained bicyclic system would form at room temperature in water might at first appear unusual; however, a similar bicyclic system was isolated in the alternate synthesis of the N-substituted hydantoin (11).

Conclusion

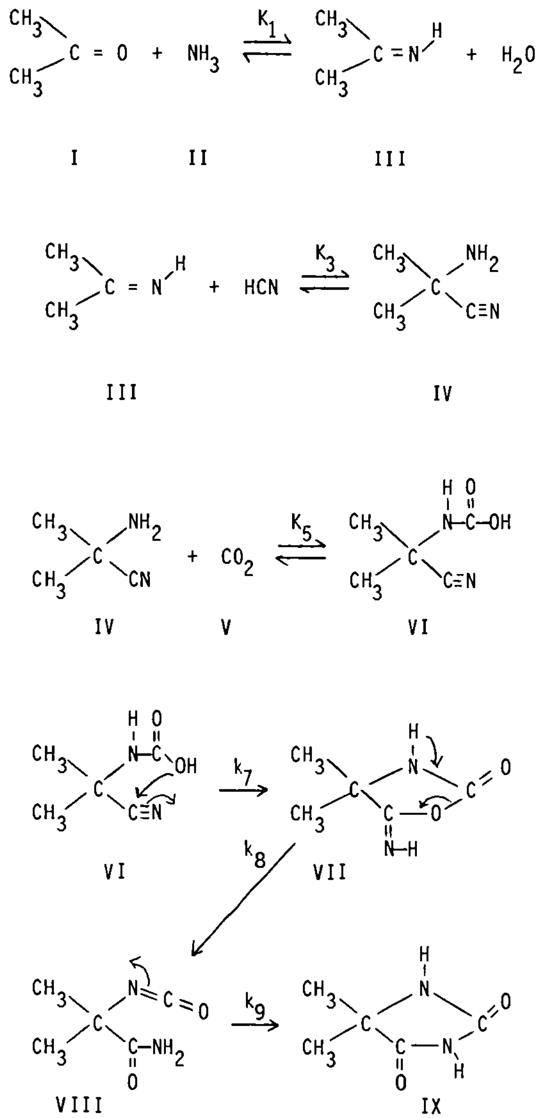
N-substituted hydantoins, specifically the N-(carbamylisopropyl)-5,5-dimethylhydantoin, form in water at room temperature from the N-α-carbamylisopropyl-N'-α-isobutyronitrile urea. Only a small amount of the 5,5-dimethylhydantoin, IX, is produced from the N-substituted urea, XI, or its carbamate salt, X. Thus, they are not likely intermediates in the formation of the DMH in water in the presence of acetone, hydrogen cyanide, carbon dioxide, and ammonia. Instead the hydantoins are believed to result from the hydrated conjugate base of the carbamic acid (VI) (Scheme 1).

Acknowledgement

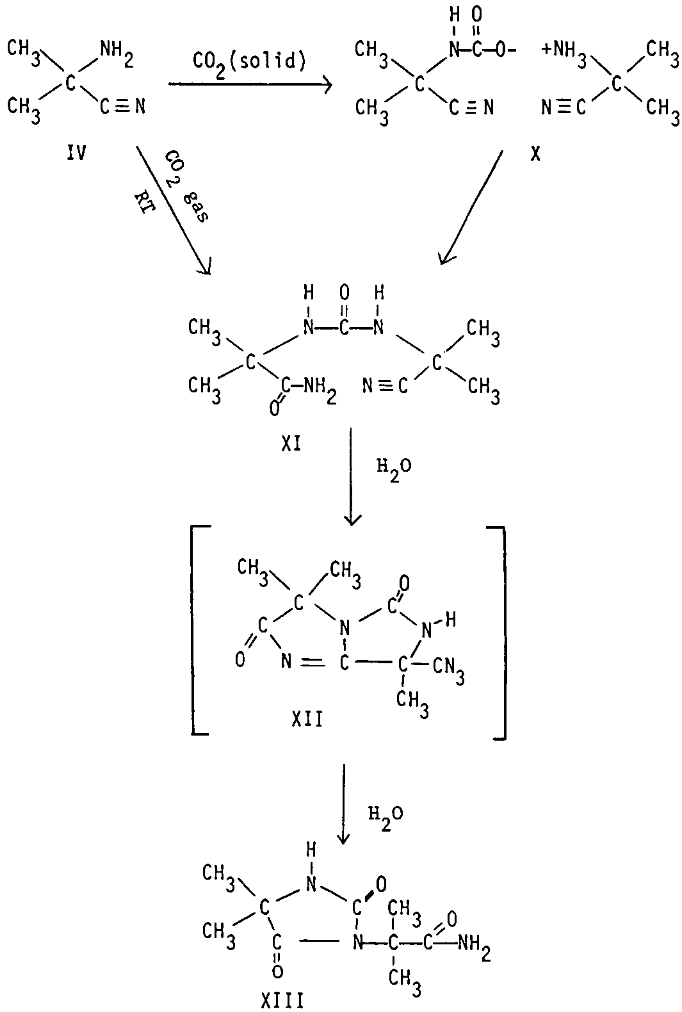
The advise of Dr. Warrack Willson, Manager of the Coal Conversion Research Division at the University of North Dakota Energy Research Center and the support from the U.S. DOE Grand Forks Project Office was appreciated.

References

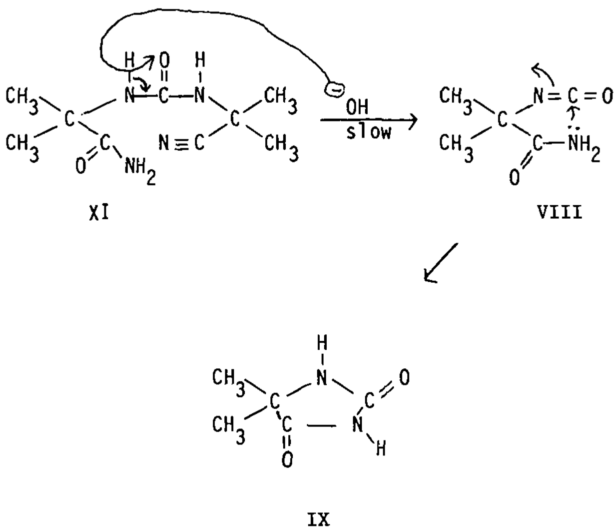
1. Ware, E. Chem. Rev., 1950, 47, 438.
2. Dorfman, R.I. "Encyclopedia of Chemical Technology", 3rd Ed., Vol. 12, John Wiley, NY, 1978, p. 692.
3. Olson, E.S., Diehl, J.W., and Miller, D.J. Anal. Chem, 1983, 55, 1111.
4. Mohr, D.H. and King, J.C., Environ. Sci. Technol., 1985, 19, 929.
5. Private Communication - Proprietary Information from Privately Owned International Gasification Corporations.
6. Olson, E.S., Worman, J.J., and Diehl, J.W. "The Formation of Hydantoins in Gasifier Condensate Water", American Chemical Society Division of Fuel Chemistry Preprints, 1985, 30 (2), 288.
7. Diehl, J., Olson, E., and Worman, J., Fuel, 1985, 64, 1019.
8. Bucherer, H.T. and Steiner, W.J., J. Pract. Chem., 1934, 140, 291.
9. Taillades, J. and Commeyras, A., Tetrahedron, 1974, 30, 3407.
10. Rousset, A., Lasperas, M., Taillades, J., and Commeyras, A., Tetrahedron, 1980, 36, 2649.
11. McKay, A.F., Paris, G.Y., and Garmaise, D.L., J. Am. Chem. Soc., 1958, 80, 6276.
12. Caplow N, J. Am. Chem Soc., 1968, 90, 6795 and references therein.
13. Nelson, D.A. and Worman, J.J., Tetrahedron Letters, 1966, 507.



Scheme 1. Mechanistic sequence for formation of DMH



Scheme 2. Mechanistic Pathway for the formation of the N-substituted hydantoin 3-(α-carbamylisopropyl)-5,5-dimethylhydantoin (XIII)



Scheme 3. Possible mechanistic pathway for the formation of 5,5-Dimethylhydantoin from N-α-carbamylisopropyl-N' -α-isobutyronitrile urea (XI)